2 MINERνA Physics Goals and Detector Design Drivers

2.9 Neutrino Scattering and Long-Baseline Oscillation Experiments

The field of oscillation physics is about to make an enormous leap forward in statistical precision: first with MINOS in the coming year, and later in T2K and the proposed NOνA experiment. Unfortunately, our relatively poor understanding of neutrino interaction physics in the relevant energy range of these experiments gives rise to systematic uncertainties that could be as large as, or even larger than, their corresponding statistical uncertainties. We have studied the origin of some of these systematic effects, and how MINERνA's measurements can reduce them to well below the statistical level.

2.9.1 Introduction

Over the past five years the field of neutrino oscillations has moved from seeing decades-old anomalies in cosmic ray [1] and solar [2] neutrino data to powerful cross checks of these anomalies (SNO data [3] and angular distributions in atmospheric neutrino data [4]), and most recently to terrestrial confirmation of the oscillation hypothesis (Kamland [5] and K2K [6]). The next steps in this field are to move to precision measurement of the mass splittings and mixing angles already observed, and search for other non-zero off-diagonal elements in the neutrino mixing matrix.

New, extremely-intense beams have been built or planned are greatly increase the statistical reach and ultimate measurement precision for oscillation parameters. With these tremendous improvements in statistical accuracy, however, come new concerns about systematic uncertainties that until now have been a secondary concern. In particular, uncertainties in neutrino cross-sections and nuclear effects lead to systematic uncertainty in the extraction of mixing parameters. Although near detectors are a critical part of precision long-baseline oscillation measurements, they are often ill-suited to make the needed cross-section measurements because they tend to be similar to the coarse and massive far detectors. A near detector can at best constrain the convolution of the near flux, cross-section and detection efficiency. Uncertainties on all of these quantities must be incorporated into the analysis. The cross-section uncertainties we consider are only a subset of the whole, but when flux and efficiency are also taken into account, near-detector performance must be worse than we estimate here.

This chapter is divided into two sections. The first addresses uncertainties relevant for ν_μ disappearance experiments, whose aim is to precisely measure the mass splitting Δm^2_{23}, and the mixing angle which has already been determined to be large, θ_{23}. To achieve these goals the experiments must measure oscillation probabilities as a function of neutrino energy. Two important concerns here are uncertainties in charged-current inelastic processes, and the scale of nuclear effects. Both inelastic channels and the nuclear environment alter the relationship between the true and measured neutrino energies. The second section discusses searches for ν_e appearance, which if observed at accelerator energies would indicate a non-zero value of θ_{13} or more exotic new physics. Because the size of the signal is unknown, the final sample may be dominated by signal (charged-current) cross-sections, and/or background (neutral- and charged-current) processes. In both cases, the experiments of the past are inadequate to precisely predict the far detector event samples.

2.9.2 ν_μ Disappearance

Precision measurement of the mass splitting between two neutrino eigenstates requires analysis of the oscillation probability as a function of neutrino energy (E_ν) divided by baseline (L). The muon neutrino disappearance probability (in the standard 3-generation oscillation parameterization [7]) is

$$P(\nu_\mu \to \nu_\mu) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right) - ... \tag{1}$$

where the additional terms are $\mathcal{O}(\sin^2 2\theta_{13})$ or smaller. Currently Δm^2_{23} is known to within a factor of two and $\cos^4\theta_{13}\sin^2 2\theta_{23}$ must be larger than 0.9, at 90% confidence level [8]. Since $\sin^2 2\theta_{13}$ has been constrained below 0.1 by the CHOOZ reactor experiment[9], this means $\sin^2 2\theta_{23}$ itself is very close to 1. The fact that θ_{23} is close to 45° has been cited as a hint of the underlying symmetry that generates neutrino mass and mixing. Precise measurement of this angle is important because the level at which the mixing deviates from maximal may again give hints about the mechanisms responsible for the breaking that symmetry [10].

More precise measurements of Δm^2_{23} are required to extract mixing angles from eventual ν_e appearance experiments. The challenge of Δm^2_{23} lies in measuring the true neutrino energy in both near and far detectors. Even if the two detectors have an identical design, any uncertainty in the "neutrino energy scale" of the ν_μ charged-current signal translates directly into an uncertainty in the extracted value of Δm^2_{23}.

There are two different ways of measuring neutrino energies: kinematic or calorimetric reconstruction. We discuss both techniques here, and then explain how uncertainties in neutrino interactions lead to energy scale uncertainties and ultimately Δm^2_{23} uncertainties.

The first experiment to provide a precision measurement of Δm^2_{23} will be MINOS [11], which has finished its first year of beam data and presented preliminary results. MINOS uses both far and near detectors, which are magnetized steel-scintillator calorimeters with approximately 6 cm total longitudinal segmentation. The transverse segmentation of the 1 cm thick scintillator planes is 4 cm. MINOS uses Fermilab's NuMI beam, with a baseline of 735 km, which can provide a variety of broad-band neutrino spectra. MINOS does most of its running in the lowest-energy configuration where the peak neutrino energy is about 3.5 GeV, but a long tail extends into tens of GeV.

T2K will use Super-Kamiokande, a water Cherenkov detector, and focus on single-ring muon-like events, for which the neutrino energy is reconstructed kinematically under the hypothesis of two-body scattering. T2K will use a narrow band off-axis neutrino beam from J-PARC in Tokai, whose peak flux is close to 700 MeV, and which originates some 295 km away [13]. The design of the near detectors has not been finalized, but should include a fine-grained tracker and a water Cherenkov detector.

The proposed NOνA experiment will use a calorimetric detector to improve measurement of Δm^2_{23}. Because NOνA is optimized for ν_e appearance rather than ν_μ disappearance, it will use near and far calorimeters made of scintillator planes interspersed with particle board or other scintillator planes. The longitudinal segmentation should be about 1/3 to 1/6 of a radiation length, and the transverse segmentation of the scintillator will be about 4 cm[12]. NOνA will also use the NuMI beam, but will place its detectors 12–14 mrad off the beam axis, to receive a narrow-band neutrino spectrum. NOνA with a baseline of 810 km, will run with a peak neutrino energy of about 2 GeV.

Kinematic neutrino energy recontruction

Kinematic reconstruction assumes that a given event was produced by a particular process (for example, quasi-elastic scattering) and determines the neutrino energy based on a sufficiently constraining subset of the final-state particles under that hypothesis.

This technique is well-suited to water Cherenkov detectors, which perform best for single-ring topologies. In Super-Kamiokande detector, for example, the ν_μ charged-current signal consists of single-ring, muon-like events, which are primarily quasi-elastic interactions. The energy of the incoming neutrino in that case can be determined using only the outgoing muon momentum (p_μ) and direction (θ_μ):

$$E_\nu = \frac{m_N E\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu} \tag{2}$$

Since the absolute energy scale for muons can be fixed to within 2–3% by a variety of calibration techniques [20], and the reconstruction algorithms measure ring directions extremely well, it seems plausible that the neutrino energy scale could be determined with comparable precision. However, not all events producing a single muon-like ring are quasi-elastic interactions. Resonant excitation, and even deep-inelastic scattering, where pions are absorbed in the oxygen nucleus or emerge below Cherenkov threshold can lead to the same topology. Such events will have a reconstructed energy well below the true neutrino energy, because the recoiling hadronic mass is larger than assumed. The effect of this inelastic background could be corrected, if the energy-dependent ratio of quasi-elastic and resonant cross-sections were perfectly known, but since it is not, an uncertainty in the effective neutrino energy scale of the detector results.

Because the ν_μ disappearance probability is nearly 100% for T2K, the relative abundance of quasi-elastic and inelastic events will be very different at Super–K than for the unoscillated beam sampled by a near detector.

Precision measurement of the differential cross-sections for single- and multi-pion production, as a function of neutrino energy, will reduce uncertainties in the subtraction of inelastic background, improving T2K's neutrino energy resolution, and ultimately the precision of its oscillation measurements. Since the event samples are so different between near and far detectors, and because water Cherenkov technology cannot entirely eliminate the inelastic background, additional measurements with fine-grained detectors are required. Ideally, these measurements would include not only exclusive inelastic reactions, but also quasi-elastic scattering, with a well-modeled efficiency relative to the inelastic channels. Because the reconstructed energy for inelastic background is lower than the true neutrino energy (the background "feeds down"), it is essential to measure these cross-sections both at and above the T2K beam energy. Chapters **??** and **??** discuss MINERνA's measurements of quasi-elastic and resonant cross-sections.

Calorimetric neutrino energy reconstruction

At neutrino energies above 1 GeV, calorimetric energy reconstruction is more efficient than kinematic reconstruction. In a low-threshold calorimetric device, the reconstructed or visible neutrino energy is simply the sum of all observed secondary particles' energies. For a ν_μ charged-current interaction, the muon energy can be determined by measuring its momentum by either range or curvature (if the calorimeter is magnetized), and the remaining activity can be summed to estimate the hadron energy. Scintillating calorimeters have a lower charged-pion detection threshold than Cherenkov detectors, so more of the total kinetic energy is visible for multi-pion interactions, which dominate the cross-section above a few GeV. As a result, neutrino energy reconstruction is less susceptible to bias from inelastic reactions than Cherenkov detectors.

For MINOS, the absolute energy scale for muons is fixed by knowledge of the steek plate thickness and muon energy loss processes. The thickness of each plate has been measured to better than 0.1% and they vary with an RMS of 0.4% [21]. In a muon test beam at CERN a 2% absolute scale calibration was achieved [22]. The hadronic and electromagnetic energy scales have been calibrated with test beams on a prototype detector at CERN, and have been measured relative to the muon scale within better than 5% [23, 24]. It is still necessary to translate from the raw response to pions and muons to the energy of interacting neutrinos, however.

At neutrino energies of a few GeV and below, three effects become significant in translation between visible and and neutrino energies. Uncertainties in these effects must be understood and included in any precise measurement of Δm^2_{23}. One effect, independent of the target nucleus, is the rest masses of the secondary charged pions. Since MINOS lacks the granularity to measure the multiplicity of final state particles, a hadron-energy dependent multiplicity distribution must be assumed. The second and third effects are due to secondary particle scattering or complete absorption in the nucleus. All three effects reduce the visible hadronic energy, which in turn lowers the reconstructed neutrino energy. Importance of these effects grows larger as the parent neutrino energy decreases,[14] due to strong enhancement of the pion–nucleon cross-section near the $\Delta(1232)$ resonace [26].

To quantify the magnitude of nuclear effects on measurement of Δm^2_{23} in a MINOS-like detector, a simple detector simulation was combined with the NEUGEN event generator [27] and NuMI fluxes at 735 km [28]. In this simulation the visible energy is simply defined as the sum of kinetic energies for all charged final-state particles, plus the total energy for the neutral pions, and photons, which are assumed to deposit all their energy as electromagnetic showers.

Figure 1 shows the variation of the ratio of visible to total neutrino energy for changes in nuclear absorption and scattering separately. In the plot on the left the target is assumed to be steel, and the parameter controlling pion absorption is set to zero or doubled. In the plot on the right all pion absorption is turned off, and the differences that remain are due to rescattering effects in steel, carbon, and lead. These rescattering effects have not been measured with neutrinos on high Z nuclei, so the rescattering variation can be considered as an error on extrapolation from the low-Z measurements that do exist. Because the ν_μ disappearance probability should be large, the far and near detector energy spectra will be very different, and these effects will only partially cancel in a ratio between near and far detectors. The extent to which they do not cancel represents a systematic error on Δm^2_{23}.

If these pion absorption Z extrapolation effects are treated as the total systematic uncertainty due to nuclear effects, we can compare it to the expected MINOS statistical error. In this more complete analysis, the detector acceptance must also be taken into account. One cut which could reduce the error due to nuclear effects significantly would be to require a minimum muon energy. The less visible energy attributable to hadrons, the smaller the relative effect of nuclear uncertainties on the total neutrino energy measurement. Requiring the muon to take up most of the energy in an event lowers efficiency, of course, and reduces the statistical power of the far-detector data sample. Here a minimum muon energy of 0.5 GeV was required, in an attempt to approximate the acceptance of a real analysis.

If the uncertainties from nuclear effects correspond to the differences in Figure 1, then for a 0.5 GeV muon momentum cut they induce a Δm^2_{23} error only slightly smaller than the statistical error expected by MINOS with 9×10^{20} protons on target (POT) (see Figure 2). This figure includes an estimate for the total systematic error that was made before the current MINOS result, where they report an additional large systematic due to the neutral current background [15]. We are currently reviewing how the NC error profile might be reduced with additional effort by MINOS and/or input from MINERνA.

MINERνA's contribution to reducing the rescattering errors would be very significant if the other

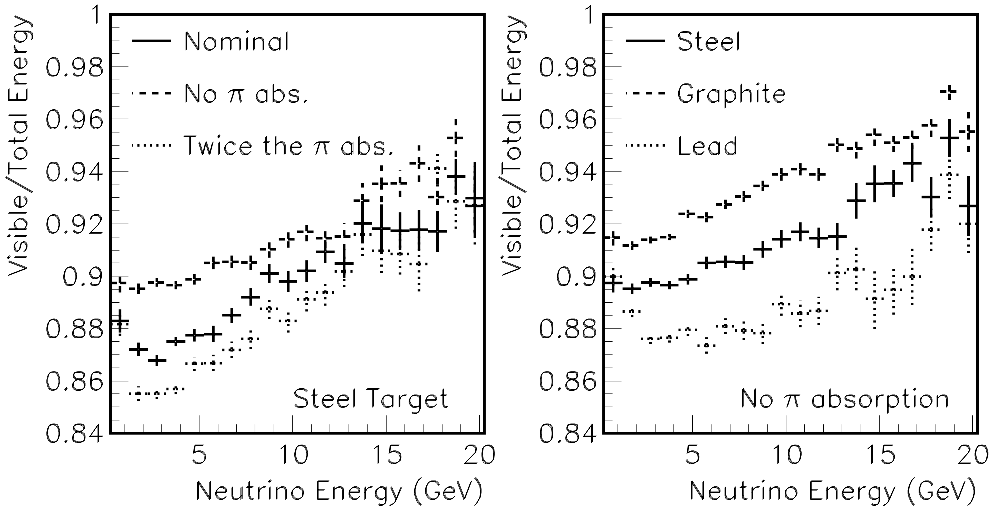

Figure 1: Ratio of visible (reconstructed) to true neutrino energy for several different models of nuclear effects. The left plot shows the ratio for steel (solid) with the nominal pion absorption, as well as the same ratio for the pion absorption turned off or doubled from what is expected. The right plot shows the differences the ratio for three different target nuclei, where pion absorption is turned off to isolate the effects of pion rescattering.

large NC systematic error is reduced. It would have the same effect on the total error as obtaining 40% more protons on target. This is illustrated in the bottom plot in Figure 2, which shows the increased *effective* protons on target as a function of the true value for Δm^2. For a mass splitting near the MINOS best fit value of 2.7×10^{-3} eV^2, this is nearly 4×10^{20} POT, roughly an extra year of beam operation.

As described in Chapter **??**, MINERνA will measure neutrino interactions on steel, carbon, and lead and collect between 400k and 2.5M events on each target (in addition to events on plastic CH) over a four year run. This represents an enormous improvement in both the statistics and the range of target nuclei over previous experiments, and would improve our level of understanding of nuclear effects dramatically. This is true with only a single year of operation, which would be the one relevant for the result from the full MINOS data. With sufficient data on several different nuclei, the error on Z extrapolation would be reduced since the nuclear models would be better constrained. The remaining uncertainties on the detector energy scale are likely due to uncertainties in pion rescattering in steel. Systematic uncertainty in Δm^2_{23} with this new data in hand would be small compared to the statistical error.

2.9.3 ν_e Appearance

Signal and backgrounds

The goal of the next generation of neutrino oscillation experiments is to determine whether the last unmeasured neutrino mixing matrix element, (called $|U_{e3}|$ or $\sin\theta_{13}$) is non-zero. If θ_{13} is in fact non-zero future experiments could measure the neutrino mass hierarchy search for CP violation in the lepton sector. T2K and NOνAwill probe this matrix element by measuring the $\nu_\mu \to \nu_e$ oscillation probability

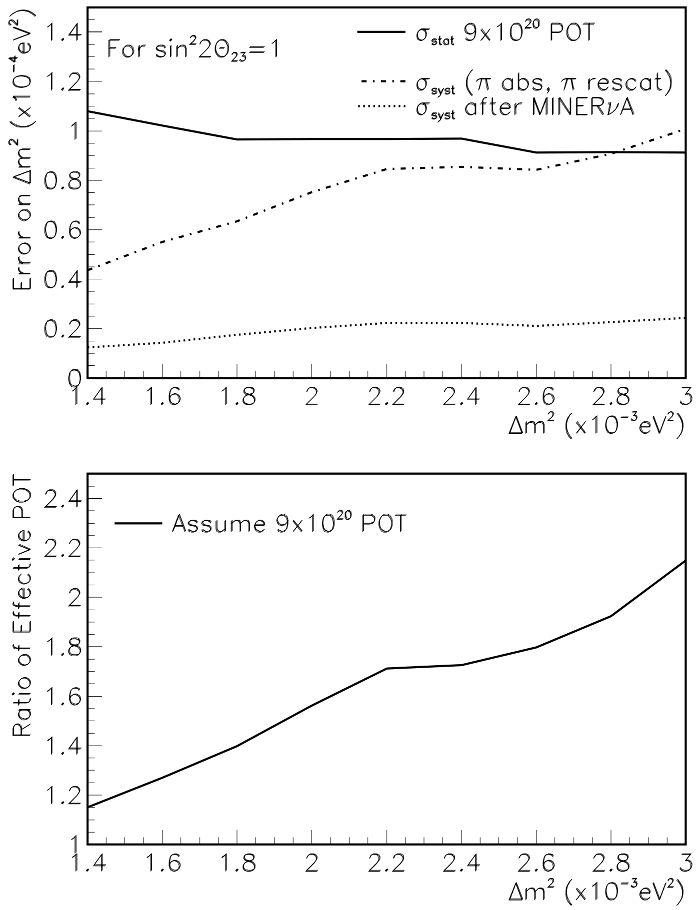

Figure 2: Top plot: projected size of errors on Δm^2 when MINOS has 9×10^{20} POT. Solid line is the expected statistical error. The other lines are estimates for the total systematic error before and after the reduction of the pion rescattering and absorption errors. Bottom plot, for the range of mass splittings near the MINOS value of 2.7×10^{-3} eV^2, this has the same effect on the total error as 40% more protons on target. These estimates were made before the current MINOS result, which reports an additional large systematic due to the neutral current background.

at a "frequency" corresponding to Δm^2_{23}. The oscillation probability for $\nu_\mu \to \nu_e$ in vacuum can be expressed [7]

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right) + ... \tag{3}$$

where the additional terms not shown are due to small effects from the solar mass splitting, Δm^2_{12}.

Identifying ν_e appearance in a ν_μ beam is quite challenging for several reasons. From the CHOOZ reactor neutrino limit on $\sin^2 2\theta_{13}$ [9] the appearance probability must be less than about 5% at 90% confidence level. Also, the beams contain an intrinsic ν_e contamination as large as a few per cent.

Finally, neutral-current and high-y charged-current ν_μ interactions can produce energetic π^0, leading to electromagnetic showers that may resemble a ν_e charged-current event.

T2K and NOνA will reduce some of these backgrounds significantly below the level in current long baseline experiments by using detectors optimized for electron appearance, and by placing those detectors off the beam axis. In two-body decay of the charged pion, the neutrino energy spectrum at small angles from the beam axis are narrower than the on-axis spectrum. Also, at these small angles the peak energy itself is reduced. The narrowest neutrino energy spectrum occurs when the far detector is placed at an angle corresponding to 90° in the pion center of mass. In this configuration, the ν_e flux comes from the three-body muon decays, so the intrinsic ν_e flux at lower energies does not increase at higher angles like the ν_μ flux does. Also, the neutral-current background is always a steeply falling function of visible energy because the outgoing neutrino always takes some fraction of the incoming neutrino's energy.

With this "off-axis" strategy, T2K and NOνA still expect some background after all analysis cuts, even in the absence of $\nu_\mu \to \nu_e$ oscillation. Measurement of the $\nu_\mu \to \nu_e$ probability requires accurate knowledge of this remaining background, and the cross-section and detection efficiencies for the ν_e signal.

Cross-section uncertainties with a near detector

Both T2K and NOνA will use near-detector measurements to predict the expected backgrounds at the far detector. In T2K, an on-axis near detector 280 m from the proton target will measure the spectrum and transverse beam profile, and at least one other off-axis detector will be focused on cross-section measurements. There are also plans to build a water Cherenkov detector 2 km from the proton target, but even then near- and far-detector efficiencies may not be identical. For NOνA, the near detector will be very similar in design to the far detector, and can be placed in a wide range of angles with respect to the beam. By making the near detector similar, NOνA hopes to minimize uncertainties in the detector response and efficiency. However, because the near detector will be as coarse as the far, it is not optimized for cross-section measurements.

To see how any uncertainties (cross-section, detector acceptance, or flux) will arise in the far detector prediction based on the near detector data, it is useful to think about how the event samples are likely to change between near and far. At a near detector, the flux of muon neutrinos will have a very strong peak at a particular energy, while at the far detector that peak will (by design) have oscillated to mostly ν_τ. At these energies, ν_τ cannot produce charged-current interactions, only neutral-current. Neutral-current samples are likely to be similar from near to far, provided the near detector is at a similar off-axis angle. Electron neutrino events at the peak are primarily from muon decays in the beam, which occur on average substantially farther downstream than the pion decays. Therefore, the extrapolation from the near to far detector tends to be different for all three event samples. If the relative population of the background sample among different categories cannot be predicted accurately (due to cross-section, detector or flux uncertainties), the far detector extrapolation will be wrong.

The MINOS and NOνA near detectors will both provide important constraints on neutrinos coming from NuMI. However, neither will be able to measure the charged- and neutral-current near detector backgrounds precisely. A finer-grained detector with improved timing resolution will be extremely useful to distinguish these two contributions which change so dramatically between near and far detectors.

A quantitative case study of how cross-section uncertainties may not completely cancel between near and far detectors, was performed using the simulation for an early design [29] of NOνA. Although

NOνA's final design will be different, the fundamental arguments remain unchanged: the mixture of contributing cross-sections at the far detector cannot, even in principle, be identical to the mixture at the near detector.

		QE	RES	COH	DIS
		cross-section Uncertainty			
		20%	40%	100%	20%
Process	Statistics	Composition after all cuts in far detector			
Signal ν_e	175 ($\sin^2 2\theta_{13} = 0.1$)	55%	35%	n/I	10%
NC	15.4	0	50%	20%	30%
$\nu_\mu CC$	3.6	0	65%	n/I	35%
Beam ν_e	19.1	50%	40%	n/I	10%

Table 1: Rate of signal and background processes in a 50 kton NOνA far detector, assuming $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2. Also listed are the present cross-section uncertainties for those processes. Charged-current coherent production was not included since it is should be unimportant compared to other charged-current processes.

The signal and background samples for the nominal 5 year run are listed in Table 1 along with the fractional contribution of each process to events of a given type passing all cuts, and the relative cross-section uncertainties [30]. Without a near detector, the total error on the background prediction from cross-section uncertainties, in the absence of ν_μ oscillation, is 16%, which is equal to the statistical error. For oscillation at the level indicated in the table, the statistical error on the probability would be 8%, while the errors from cross-section uncertainties alone are 31% .

Figure 3 shows the projected error on $\sin^2 2\theta_{13}$ as a function of $\sin^2 2\theta_{13}$ itself, for present cross-section uncertainties. Should NOνA find a large signal, even in its first phase the measurement will be systematics limited with existing knowledge of relevant cross-sections. Chapters **??**, **??**, and **??** explain how different channels will be isolated, and give the size of the expected samples. MINERνA should be able to reduce cross-section uncertainties for NOνA to about 5% for all charged- and neutral-current deep-inelastic scattering processes, 10% for neutral-current resonant processes, and 20% for neutral-current coherent π^0 processes. If these uncertainties were achieved, then systematic errors due to cross-section uncertainties would be well below the statistical errors, as shown in Figure 3.

2.9.4 Conclusions

It is clear from even these preliminary studies that MINERνA will play an important and potentially decisive role in helping current and future precision oscillation experiments reach their ultimate sensitivity. To get the most precise values of Δm^2_{23} (which is eventually necessary to extract mixing angles and the CP-violating phase) our field must better understand and quantify the processes that occur between interaction of an incoming neutrino and measurement of the outgoing particles in a detector. Although the issues are different depending on whether the detector is a water Cherenkov or calorimetric devices, in both cases more information is needed. Extracting mixing parameters like θ_{13} and ultimately the neutrino mass hierarchy and CP-violation requires much better understanding of resonant cross-sections. Even setting limits on these parameters will require better measurements of neutral-current processes.

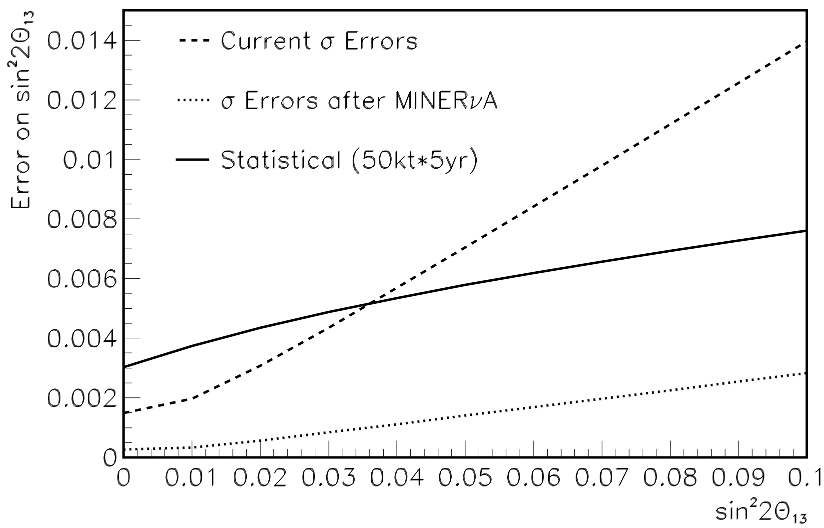

Figure 3: Statistical error, present cross-section systematic error, and post-MINERνA cross-section systematic error in NOνA measurement of $\sin^2 2\theta_{13}$, as a function of $\sin^2 2\theta_{13}$.

The cost of curing our present ignorance pales in comparison to the possibility that an entire generation of oscillation experiments might miss out on an exciting discovery or end in a morass of inconclusive, ambiguous, contradictory or even wrong results because we have failed to invest the effort needed to understand the most basic interactions of the particle whose exotic behavior they were built to study. Precision measurement of exclusive cross-sections and nuclear effects will finally put a field making tremendous strides in luminosity and statistical power on a sound systematic foundation.

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